APPLICATION

FOR

UNITED STATES LETTERS PATENT

TITLE: VOLTAGE REGULATOR

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VOLTAGE REGULATOR

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001]   This application claims the benefit of the filing date of U.S. provisional application No. 60/496,957 filed August 21, 2003, the entire contents of which are herein incorporated by reference.

TECHNICAL FIELD

[0002]   An aspect of this invention relates to power systems for electronic circuits.

BACKGROUND

[0003]   Modern digital logic devices are now being built using 0.13 um process or smaller technology. These small process devices operate at extremely low voltages, much lower voltages than have been previously used for most devices. In the near future, operation below 1 volt will probably be commonplace. One of the challenges in systems that use these low voltage devices is how to cost effectively interface the main source of energy, such as the 5 volt or 12 volt power supply found in typical systems, to the sub 1 volt devices.

[0004]   In particular, traditional non-isolated buck DC/DC converters may be too inefficient for converting a 12 volt supply to a 1 volt supply. To regulate an output voltage,

traditional buck converters may vary the pulse width of the
conduction cycle. To convert 12 volts to 1 volt, the duty
cycle of traditional non-isolated buck DC/DC converters may be
very small, leading to high conversion losses and low power
efficiency.

SUMMARY

[0005]   A regulator for converting energy from an input
source to a voltage of an output. The regulator comprising at
least two conduction switches to conduct energy from the input
source to the output. Each of the conduction switches
operated at approximately 50% duty cycle. At least two
inductors in communication with the at least two conduction
switches, the at least two inductors wound together on a
common core and each inductor having a polarity such that DC
currents in the inductors cancel each other. The inductors
having a coefficient of coupling approximately greater than
0.99. At least two freewheeling switches in communication
with the at least two conduction switches to provide a path
for current during non-conduction periods. A drive signal
generator to generate drive signals for controlling the at
least two conduction switches.

[0006]   The details of one or more embodiments of the
invention are set forth in the accompanying drawings and the

description below. Other features, objects, and advantages of the invention will be apparent from the description and drawings, and from the claims.

DESCRIPTION OF DRAWINGS

[0007]   FIG. 1A is a block diagram of an aspect of a coupled inductor regulator.

[0008]   FIG. 1B is a schematic diagram of an aspect of a conduction switch.

[0009]   FIG. 2A is a block diagram of an aspect of a 2:1 buck regulator.

[0010]   FIG. 2B is a circuit diagram of an aspect of a 2:1 buck regulator.

[0011]   FIG. 2C is a representation of waveforms associated with an aspect of a 2:1 buck regulator.

[0012]   FIG. 3A is a block diagram of an aspect of a 1:2 boost regulator.

[0013]   FIG. 3B is a circuit diagram of an aspect of a 1:2 boost regulator.

[0014]   FIG. 4A is a block diagram of an aspect of a 2:-1 buck regulator.

[0015]   FIG. 4B is a circuit diagram of an aspect of a 2:-11 buck regulator.

[0016]   FIG. 5 is a circuit diagram of an aspect of a 1:2 boost regulator having synchronous rectifiers.

[0017]   FIG. 6A is a schematic of an aspect of a buck configuration coupled inductor regulator having four coupled inductors.

[0018]   FIG. 6B is a schematic of an aspect of a boost configuration coupled inductor regulator having four coupled inductors.

[0019]   FIG. 6C is a schematic of an aspect of a flyback configuration coupled inductor regulator having four coupled inductors.

[0020]   FIG. 7A is a block diagram of an aspect of a low dropout device combined with a 2:1 Regulator.

[0021]   FIG. 7B is a schematic diagram of an aspect of a low dropout device combined with a 2:1 Regulator.

[0022]   FIG. 8 is a block diagram of an aspect of a multi-stage regulator system.

[0023]   FIG. 9A is a block diagram of an aspect of buck regulator combined with a 2:1 Regulator.

[0024]   FIG. 9B is a graphical representation of the current and power dissipation in a conduction switch of a buck converter.

[0025]   FIG. 10A is a block diagram of an aspect of multiple 2:1 Regulators combined in series with a buck regulator.

[0026]   FIG. 10B is a block diagram of another aspect of multiple 2:1 Regulators combined in series with a buck regulator.

[0027]   FIG. 11 is a block diagram of an aspect of a regulator system having multiple coupled inductor regulators.

[0028]   FIG. 12A is a block diagram of an aspect of an amplifier system.

[0029]   FIG. 12B is a block diagram of another aspect of an amplifier system.

[0030]   FIG. 13 is a block diagram of an aspect of a vehicle electrical system.

[0031]   FIG. 14 is a block diagram of an aspect of a power system for high speed drivers.

[0032]   FIG. 15A is a graphical representation of an aspect of a coupled inductor.

[0033]   FIG. 15B is a graphical representation of an aspect of a coupled inductor.

[0034]   FIG. 16A is a schematic of an aspect of a buck configuration coupled inductor regulator ·for generating an output voltage that is approximately one-fourth the amplitude of the input voltage.   .

[0035]   FIG. 16B is a timing diagram of signals corresponding to an aspect of a buck configuration coupled inductor regulator.

[0036]   FIG. 16C is a schematic of an aspect of another buck configuration coupled inductor regulator having coupled inductors.

[0037]   FIG. 17A is a schematic of an aspect of an autosensing coupled inductor regulator having for automatically controlling the amplitude of the output voltage as a function of the input voltage.

[0038]   FIG. 17B is a schematic of an aspect of an autosensing buck converter for automatically controlling the amplitude of the output voltage as a function of the input voltage.

[0039]   Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

[0040]   Figure 1 shows a block diagram of an aspect of a coupled-inductor regulator 10 for supplying power to one or more devices such as high-speed drivers and other electronic devices. The coupled inductor regulator 10 may operate open-loop to convert an input voltage, V_{DD}, to a non-isolated output voltage, V_{OUT}. The amplitude of the output voltage is approximately an integer multiple or divisor of the input voltage and may be determined by the configuration of the coupled-inductor regulator 10 and the quantity of coupled

inductors in the coupled-inductor regulator 10. For example in a buck configuration having two coupled inductors, the coupled-inductor regulator 10 may generate an output voltage that is approximately one-half of the input voltage.

[0041]   The coupled-inductor regulator 10 may include conduction switches 11, freewheeling switches 12, and two or more coupled inductors 13 arranged in a buck or boost configuration. A drive signal generator 14 may generate drive signals to control the conduction switches 11. The drive signals are controlled to generate a total conduction time approaching 100%, negating a small amount of deadtime to reduce cross-conduction between the conduction switches 11 and the freewheeling switches 12.

[0042]   A frequency generator 15 may generate a clock signal having an operating frequency. The drive signals may be synchronized to operate at the operating frequency. In one aspect, the operating frequency may be fixed to a predetermined frequency. In another aspect, the operating frequency may be controlled in response to changes in load conditions such as output current and output voltage. For example, when a change in the output current, such as an increase in load current, is sensed, the operating frequency may be increased to increase the transient response of the output. Once the coupled inductor regulator 10 has responded

to the change in load condition and has reached steady-state

operating conditions again, the operating frequency may be

decreased to reduce power losses in the coupled inductor

regulator 10.

[0043]   The coupled inductors 13 may be tightly coupled

together preferably having a coefficient of coupling, K, of

approximately one, where unity is the ideal value. Preferably

the inductors 13 are wound together on a common magnetic core

to form an inductor assembly that provides the maximum value

of coefficient of coupling. The coefficient of coupling is

approximately one being at least 0.9 and preferably greater

than 0.99. The polarity for each of the windings for the

coupled inductors 13 are selected so that DC currents flowing

through the coupled inductors 13 approximately cancel, leading

to approximately zero DC current flowing through the magnetic

core of the inductor assembly. Since there is virtually no DC

current flowing through the inductor assembly, a smaller core

size may be used for the coupled inductors resulting in a

smaller size (volume) and lower cost for the inductor

assembly. In addition, high permeability core materials may

be used for the magnetic core such as ferrites having shapes

such as bead and toroid. Lower permeability materials may

also be used such as MPP cores, ferrite PQ cores, and other

split core shapes.

[0044]   In addition to the steady-state advantages obtained

by maximizing the coefficient of coupling between the coupled

inductors, the transient response of the coupled inductor

regulator 10 may also be improved. During a transient, the

high mutual coupling between the coupled inductors may

effectively cancel the inductance of the individual inductors

as far as the transient load current is concerned.

[0045]   Figure 1B shows an aspect of one of the conduction

switches 11 included in the coupled inductor regulator 10.

Each of the conduction switches 11 may be comprised of one or

more parallel switches, 16a-16c, that are independently

controllable. Each of the parallel switches 16a-16c may be

controlled by enable signals, ENB1-ENB3, to enable either all

or a subset of the parallel switches 16a-16c. The enabled

parallel switches 16a-16c may then controlled by the same

drive signal, Φ_1.

[0046]   The conduction switches 11 may also be driven using

a multi-level gate voltage to reduce switching losses. For

example, the amplitude of the on voltage may be adjusted to

differing predetermined levels dependent on factors such as

the current flowing through the conduction switch to decrease

switching losses in the conduction switch.

[0047]   Figure 2A shows an aspect of a 2:1 regulator 20 that

may be an embodiment of the coupled inductor regulator 10.

The 2:1 regulator 20 may operate open-loop to convert an input voltage, V_{DD}, to a non-isolated output voltage that is approximately one-half the amplitude of the input voltage.

[0048]   Figure 2B shows a schematic diagram of an aspect of the 2:1 regulator 20. The 2:1 regulator 20 may include two buck converters operating 180 degrees out of phase to generate an output voltage, Vout, from an input voltage. The input voltage may be a high-side voltage, V_H, referenced to ground or to some other voltage such as a low-side voltage, V_L. Each buck converter may include a conduction switch 22a and 22b, a free-wheeling switch 24a and 24b, and an inductor 26a and 26b. An output capacitor 28 may filter the output voltage for each of the buck converters. The value of the output capacitor 28 may be decreased since there is negligible ripple current. In addition, due to the tight coupling between the output and the input of the 2:1 regulator 20, any capacitance at the input works in concert with the output capacitance 28 to effectively provide parallel capacitance to a load at the output.

[0049]   The inductors, 26a and 26b, may be tightly coupled together preferably having a coefficient of coupling, K, of approximately one, where unity is the ideal value. Preferably the inductors 26a and 26b are wound together on a common magnetic core to form an inductor assembly 27 that provides a high value of coefficient of coupling between the inductors

26a and 26b. The polarities of the inductor windings are selected so that the DC currents flowing through the inductors 26a and 26b approximately cancel so that approximately zero DC current flows through the magnetic core of the inductor assembly 27. Therefore, a smaller core size with a low permeability material may be used for the inductors 26a and 26b, resulting in a smaller size (volume) and lower cost for the inductor assembly 27. In addition, the transient response of the 2:1 buck regulator 20 is improved due to cancellation of the individual inductances as far as transient load currents are concerned.

[0050] Any type of switches may be used for the free-wheeling switches 24a and 25b such as synchronous rectifiers and discrete rectifiers.

[0051] Using a two level gate voltage for the conduction switches 22a and 22b is particularly advantageous with the 2:1 buck converter 20 since the output voltage, $V_{DD}/2$, may be used as the intermediate level voltage for driving the conduction switches.

[0052] Figure 2C shows waveforms associated with an aspect of the 2:1 Regulator 20. Each of the conduction switches 22a and 22b are controlled by drive signals that are operated approximately 180 degrees out-of-phase. The first conduction switch 22a may be driven by a signal Φ_1, 30, that is

approximately a square-wave. The second conduction switch 22b

may be driven a second signal $\overline{\Phi_1}$, 32, that is approximately

the inverse of signal Φ_1, 30. A minimal amount of deadtime

may be included between Φ_1 and $\overline{\Phi_1}$ to decrease any shoot-

through currents that may flow from the conduction switches

22a and 22b through the freewheeling switches 24a and 24b

during switching transitions. The amount of deadtime may be

minimized to decrease the ripple current and to improve the

transfer of energy to the output. When the first conduction

switch 22a is conducting, the current, I1, 34 flowing through

the output inductor 26a increases at a linear rate.

Similarly, when the second conduction switch 22b is

conducting, the current, I2, 36 flowing through the output

inductor 26b increases at a linear rate. Since the combined

conduction time of the conduction switches 22a and 22b

approaches 100%, the amplitude of the ripple current flowing

to the output capacitor 28 is negligible, leading to a smaller

output capacitor 28 for filtering the output.

[0053]   Figure 3A shows an aspect of a 1:2 Regulator 50 that

may be an embodiment of the coupled inductor regulator 10.

The 1:2 regulator 50 may operate open-loop to convert an input

voltage, V_{DD}, to a non-isolated output voltage that is

approximately twice the amplitude of the input voltage.

[0054]   Figure 3B shows a schematic diagram of an aspect of

the 1:2 regulator 50. The 1:2 regulator 50 may include two

boost converters operating 180 degrees out of phase to

generate an output voltage, Vout, from an input voltage. The

input voltage may be a high-side voltage, V_H, referenced to

ground or to some other voltage such as a low-side voltage,

V_L. Each boost converter may include a conduction switch 52a

and 52b, a free-wheeling switch 54a and 54b, and an inductor

56a and 56b. An output capacitor 58 may filter the output

voltage for each of the boost converters. Similar to the 2:1

regulator 20, the value of the output capacitor 58 may be

decreased since there is negligible ripple current, and due to

the tight coupling between the output and the input of the 1:2

regulator 50, any capacitance at the input works in concert

with the output capacitance 58 to effectively provide parallel

capacitance to a load at the output.

[0055]   Each of the conduction switches 52a and 52b are

controlled by drive signals that are operated approximately

180 degrees out-of-phase. The first conduction switch 52a may

be driven by a signal Φ_I that is approximately a square-wave.

The second conduction switch 52b may be driven a second signal

$\overline{\Phi_I}$ that is approximately the inverse of signal Φ_I. A minimal

amount of deadtime may be included between Φ_I and $\overline{\Phi_I}$ to

decrease any shoot-through currents that may flow from the

conduction switches 52a and 52b through the freewheeling

switches 54a and 54b during switching transitions. The amount

of deadtime may be minimized to decrease the ripple current

and to improve the transfer of energy to the output. Since

the combined conduction time of the conduction switches 52a

and 52b approaches 100%, the amplitude of the ripple current

flowing to the output capacitor 58 is negligible, leading to a

smaller output capacitor 58 for filtering the output.

[0056]   The inductors, 56a and 56b, for each of the boost

converters may be tightly coupled together preferably having a

coefficient of coupling, K, of approximately one. The

inductors 56a and 56b may be wound together on a single

magnetic core to form an inductor assembly 57 that provides a

high value of coefficient of coupling. The benefits of having

a high coefficient of coupling are similar to those of the 2:1

regulator 20 and the coupled inductor regulator 10.

[0057]   Any type of switches may be used for the free-

wheeling switches 54a and 55b such as synchronous rectifiers

and discrete rectifiers.

[0058]   Figure 4A shows an aspect of a 1:-1 regulator 60

that may be an embodiment of the coupled inductor regulator

10. The 1:-1 regulator 60 may operate open-loop to convert an

input voltage, V_{DD}, to a non-isolated output voltage that is approximately the negative of the input voltage.

[0059]   Figure 4B shows a schematic of an aspect of the 1:-1 regulator 60. The 1:-1 regulator 60 is similar to the 2:1 regulator 20 in function with corresponding elements numbered in the range 60-68, except that the 1:-1 regulator 60 may include two flyback regulators operating at approximately 50% duty cycle to generate an output that is the negative of the input voltage.

[0060]   Figure 5 shows an aspect of a coupled inductor regulator 70 that is similar to 1:2 regulator 50 in function with corresponding elements numbered in the range 70-78, except that the coupled inductor regulator 70 includes synchronous rectifiers 74a and 74b to rectify the output signals from the conduction switches 72a and 72b. The synchronous rectifiers 74a and 74b may advantageously reduce losses associated with rectifying the output signals, thereby increasing the energy efficiency of the coupled inductor regulator 70. Although the synchronous rectifiers are illustrated as included in the boost configuration of the coupled inductor regulator, the synchronous rectifiers may be used as the freewheeling rectifiers in any embodiment of the coupled inductor regulator 10.

[0061]   Figure 6A shows another aspect of a coupled inductor regulator 120 for converting an input voltage to an output voltage, Vout. The coupled inductor regulator 120 is similar to the 2:1 regulator 20 in function with corresponding elements numbered in the range 120-128, except that the coupled inductor regulator 120 includes four coupled inductors 126a-126d having a coefficient of coupling approaching 1. Each of the coupled inductors 126a-126d may be wound with a predetermined number of turns, N1-N4 so that each of the coupled inductors may have an individually controllable number of turns. The ratio of the turns of each coupled inductor to the other coupled inductors may be varied to control the amplitude of the output voltage, Vout. For example, in one aspect the turns may be set so that N1=N2=N3=N4, in which case the amplitude of the output voltage will be approximately equal to one-fourth of the input voltage. In another aspect the turns may be set so that N1=N2, N3=N4, and N1=2*N3, in which case the amplitude of the output voltage will be approximately equal to one third of the input voltage.

[0062]   Figure 6B shows another aspect of a coupled inductor regulator 130 for converting an input voltage to an output voltage, Vout. The coupled inductor regulator 130 is similar to the 1:2 regulator 50 in function with corresponding elements numbered in the range 130-138, except that the

coupled inductor regulator 130 includes four coupled inductors 136a-136d having a coefficient of coupling approaching 1. Each of the coupled inductors 136a-136d may be wound with a predetermined number of turns, N1-N4 so that each of the coupled inductors may have an individually controllable number of turns. The ratio of the turns of each coupled inductor to the other coupled inductors may be varied to control the amplitude of the output voltage, Vout.

[0063]   Figure 6C shows another aspect of a coupled inductor regulator 140 for converting an input voltage to an output voltage, Vout. The coupled inductor regulator 140 is similar to the 1:-1 regulator 60 in function with corresponding elements numbered in the range 140-148, except that the coupled inductor regulator 140 includes four coupled inductors 146a-146d having a coefficient of coupling approaching 1. Each of the coupled inductors 146a-146d may be wound with a predetermined number of turns, N1-N4 so that each of the coupled inductors may have an individually controllable number of turns. The ratio of the turns of each coupled inductor to the other coupled inductors may be varied to control the amplitude of the output voltage, Vout.

[0064]   Figure 16A shows an aspect of a 4:1 regulator 150 for generating an output voltage, Vout, from an input voltage, Vin. The 4:1 regulator 150 may operate open-loop to generate

Vout as a non-isolated voltage that is approximately one-fourth the amplitude of Vin. The 4:1 regulator 150 may include four drivers 152a-152d to buffer phase signals, φ1-φ4, corresponding to each of the drivers 152a-152d. The drivers 152a-152d may be in communication with six coupled inductors 156a-156f arranged in a lattice network.

[0065]   Pairs of the coupled inductors 156a-156b, 156c-156d, and 156e-156f may each be tightly coupled together preferably having a coefficient of coupling, K, of approximately one. Preferably each pairs of inductor 156a-156b, 156c-156d, and 156e-156f is wound together on a corresponding common magnetic core to form inductor assemblies that may provide a high value of coefficient of coupling between the inductors 156a-156b, 156c-156d, and 156e-156f. The polarities of the inductor windings are selected so that the DC currents flowing through each pair of inductors 156a-156b, 156c-156d, and 156e-156f approximately cancel so that approximately zero DC current flows through the magnetic core of the corresponding inductor assembly. In another aspect, all of the inductors 156a-156f may be wound on a single magnetic core.

[0066]   The drivers 152a-152d may advantageously be included on a single semiconductor die to reduce cost, or decrease the volume of the 4:1 regulator. The phase signals each may have an on-state and an off-state, and a duty cycle of

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approximately 25%. The phase signals may be arranged in a

timing sequence such as in one aspect, an alternating timing

sequence, PS1, and in another aspect the phase signals may be

arranged in a sequential timing sequence, PS2. In the

alternating timing sequence PS1, phase signals φ1-φ3-φ2-φ4

respectively are applied to the drivers 152a-152b-152c-152d

(see Figure 16B). In the sequential timing sequence PS2,

phase signals φ1-φ2-φ3-φ4 respectively are applied to the

drivers 152a-152b-152c-152d. The coupled inductors 156a-156f

preferably have a coefficient of coupling approaching 1 and

may be wound with approximately an equal number of turns on

the same magnetic core structure. An output capacitor 158 may

filter the output voltage to reduce noise and ripple voltage.

Similar to the 2:1 regulator 20 the value of the output

capacitor 158 may be decreased since there is negligible

ripple current, and the capacitance at the input works in

concert with the output capacitance.

[0067]   Figure 16B shows signals and waveforms associated

with an aspect of the 4:1 regulator 150. The phase signals,

φ1-φ4, show the timing relationship between each of the

phases, φ1-φ4. Each of the phases, φ1-φ4, may have a duty

cycle of approximately 25% and an amplitude of approximately

Vin. Signal PS2-A shows the waveform at node A of Figure 16A

when the PS2 phase sequence of the phase signals, φ1-φ4 is

applied to the drivers 152a-152d. Signal PS2-B shows the

waveform at node B of Figure 16A when the PS2 phase sequence

of the phase signals, φ1-φ4 is applied to the drivers 152a-

152d. The amplitude of signals PS2-A and PS2-B may be

approximately Vin/2.

[0068]   Signal PS1-A shows the waveform at node A of Figure

16A when the PS1 phase sequence of the phase signals, φ1-φ4 is

applied to the drivers 152a-152d. Signal PS1-B shows the

waveform at node B of Figure 16A when the PS1 phase sequence

of the phase signals, φ1-φ4 is applied to the drivers 152a-

152d. The amplitude of signals PS1-A and PS1-B may be

approximately Vin/2. The signal frequency of signals PS1-A

and PS1-B is approximately twice the frequency of signals PS2-

A and PS2-B leading to potentially smaller inductance values

when the PS1 timing sequence is used versus the PS2 timing

sequence.

[0069]   Figure 16C shows an aspect of a coupled inductor

regulator 160 for generating an output voltage, Vout, from an

input voltage, Vin. The coupled inductor regulator 160 is in

a buck configuration and may include multiple coupled

inductors 166 arranged in a lattice network having any

quantity of stages ranging from 1 to N. The coupled inductor

regulator 160 may operate open-loop to generate Vout as a non-

isolated voltage that is approximately equal to Vin/(2N). The

coupled inductor regulator 160 may include drivers 162 to

buffer phase signals, $\varphi_1 - \varphi_{2N}$, corresponding to each of the

drivers 162. Each of the phase signals, $\varphi_1 - \varphi_{2N}$, may have a

duty cycle of approximately (100/2N)% and an amplitude of Vin.

The phase signals may be arranged in any timing sequence such

as PS1 and PS2 as shown with the 4:1 regulator 150.

[0070]   Pairs of the coupled inductors 167 within each stage

may be tightly coupled together preferably having a

coefficient of coupling, K, of approximately one. Preferably

each pair of inductors 167 is wound together on a

corresponding common magnetic core to form inductor assemblies

that may provide a high value of coefficient of coupling

between the inductors 166. For example, stage two may have

two inductor assemblies and stage three may have four inductor

assemblies. The polarities of the inductor windings are

selected so that the DC currents flowing through each pair of

inductors 167 approximately cancel so that approximately zero

DC current flows through the magnetic core of the

corresponding inductor assembly. In another aspect, all of

the inductors 166 may be wound on a single magnetic core.

[0071]   Figure 7A shows an aspect of a regulator system 200

for generating a regulated output voltage, Vout, from an input

voltage, Vin. The regulator system 200 includes a low dropout

regulator, LDO, 202 in series with a coupled inductor

regulator 204. The LDO 202 may control the LDO output, Vx, as

a function of one or more feedback signals. In one aspect, a

feedback signal 206 from the output of the coupled inductor

regulator 204may communicate a sample of Vout to the LDO 202

to be compared to a reference voltage. The LDO 202 may

regulate the LDO voltage, Vx, as a function of comparing Vout

to the reference voltage. The coupled inductor regulator 204

may generate Vout as a function of a fixed ratio of Vx. For

example, if a 2:1 regulator is used for the coupled inductor

regulator 204, then Vout is approximately equal to one-half

the amplitude of Vx. In another example, if a 1:2 regulator

is used for the coupled inductor regulator 204, then Vout is

approximately equal to twice the amplitude of Vx. In another

aspect, multiple feedback signals may be used for multi-loop

control of the regulator system 200. Any multi-loop control

techniques may be employed such as weighted feedback signals,

selecting one feedback signal from amongst the multiple

feedback signals, and varying the response time of each

feedback loop. For example, the inner feedback loop from Vx

to the LDO 202 may be set slower than an outer loop from Vout

to the LDO 202. Any type of linear regulator may be used for

the low drop out regulator. In one aspect the LDO 202 and the

coupled inductor regulator 204 may be fabricated on a single

integrated circuit 201 with separate inductor assemblies for

the output inductors and coupled inductors. In another

aspect, the order of the coupled inductor regulator 204 and

the LDO 202 may be reversed so that the coupled inductor

regulator 204 generates the intermediate voltage, Vx, from the

input voltage, Vin, and the LDO 202 generates the output

voltage, Vout. The LDO 202 may receive a feedback signal from

Vout and a feedforward signal from the intermediate voltage.

[0072]   Figure 7B shows an aspect of a preferred embodiment

of a regulator system 210 in which a combination of a

reference amplifier 214 and Field Effect Transistor 216 form

an LDO having an LDO output, Vx. A 2:1 regulator 212

generates an output voltage, Vout, from Vx, where Vout is

approximately equal to one-half of the amplitude of Vx. An

output capacitor 214 may filter the output from the 2:1

regulator 212. The regulator system 210 advantageously only

requires the LDO to supply a current, Ix, that is one-half the

amplitude of the output current, Iout, thereby lowering the

cost of the FET 204 and heat sink requirements for the LDO. A

capacitor 218 may also be included at the output of the FET

216 to possibly improve the stability of the LDO. In one

exemplary regulator system 210, Vin may be 3.3V and Vout may

be in the range of 1.2V to 1.5V. In another exemplary

regulator system 210, Vin may 2.5V and Vout may be in the

range of 0.8V to 1.2V.

[0073]   Figure 8 shows an aspect of a two stage regulator

system 300 for generating an output voltage, Vout, that is

approximately equal to one-fourth of the amplitude of the

input voltage, Vin. A first stage 2:1 regulator 302 is

connected in series with a second stage 2:1 regulator 304.

The first stage 2:1 regulator 302 may operate at twice the

voltage, but half of the current of the second stage 2:1

regulator 304. Since the two stages 302 and 304 operate at

different voltages, the semiconductor processes used for each

of the stages 302 and 304 may be optimized for the operating

voltage. For example, the first stage 2:1 regulator 302 may

be made using a 0.5um equivalent logic transistor process,

while the second stage 2:1 regulator 304 may be made using a

0.25um equivalent logic transistor process. Selecting the

process to be used for each regulator stage based on the

voltage of the stage may be applied to any of the embodiments

of the coupled inductor regulator as well as any configuration

of coupled inductor regulators such as a combination of

series, parallel, and tapped coupled inductor regulators. By

optimizing the process that is used for each of the coupled

inductor regulators, the die size may be reduced leading to a

substantial decrease in cost.

[0074]   Figure 9A shows an aspect of a very low voltage high

current regulator 320 (VLVHC regulator) for generating a low

voltage output. The VLVHC regulator 320 may include a buck

converter 322 followed by a 2:1 regulator 324. In one aspect

the buck converter 322 and the 2:1 regulator 324 may be

fabricated on a single integrated circuit 201 with separate

inductor assemblies for the output inductors and coupled

inductors. The buck converter 322 may be any type of buck

converter such as a traditional buck converter having one or

more output phases. One or more feedback signals for

controlling the output of the buck converter 322 may be

communicated to the buck converter 322 from various points in

the VLVHC regulator 320 such as the output of the 2:1

regulator 324 and the output of the buck converter 322. Since

the output current of the buck converter 322 is half the

amplitude that it would be if a single buck converter

converted Vin directly to Vout, the output devices of the buck

converter 322 may advantageously be reduced in size by a

factor of at least 2 compared to generating Vout with only a

single buck converter. The output devices may include devices

such as output capacitors and output inductors. The invention

advantageously recognizes that the ripple voltage at the

output of the 2:1 regulator 324 will be reduced by a factor of

two from the ripple voltage at the output of the buck

converter 322, therefore smaller output devices may be used

for the buck converter 322. In addition, the volumetric

efficiency of capacitors is typically directly related to the

voltage rating of a capacitor so that typically the volume of

a capacitor decreases by $\left(V_H \middle/ V_L \right)^2$ as the voltage rating of the

capacitor rating increases, where VH is the higher voltage

rating and VL is the lower voltage rating. In addition, the

volume of inductors is directly related to the square of the

current that flows through an inductor, so that the volume of

an inductor decreases as the maximum rated current of the

inductor decreases. In one aspect, multiple feedback signals

may be used for multi-loop control of the VLVHC regulator 320.

Any multi-loop control techniques may be employed such as

weighted feedback signals, selecting one feedback signal from

amongst the multiple feedback signals, and varying the

response time of each feedback loop. For example, the inner

feedback loop from the buck converter output to the buck

converter 322 may be set slower than an outer loop from Vout

to the buck converter 322.

[0075]   In addition, the overall power efficiency of the

VLVHC regulator 320 may be lower than if only a non-isolated

buck converter were used to convert Vin to Vout. Figure 9B

shows a waveform 326 of current, Ids, flowing through a

conduction switch in a non-isolated buck converter that

generates Vout from Vin. The duty cycle in the buck converter

may be approximately four times lower than the duty cycle in
the VLVHC regulator 320. Since the duty cycle is lower, the
peak current, Ids, flowing through the conduction switch may
be approximately four times greater than the peak current
flowing through the conduction switch of the VLVHC regulator
320, leading to switching losses in the buck converter that
may be approximately four times greater the switching losses
in the buck converter of the VLVHC regulator 320. A waveform
328 of the power dissipation, Pd, in the conduction switches
of the non-isolated buck converter shows the high switching
losses occurring during switching of the conduction switches.

[0076]   Figure 10A shows another aspect of a very low
voltage high current regulator 340 (VLVHC regulator) for
generating a low voltage output. The VLVHC regulator 340 is
similar to the VLVHC regulator 320 in function, except that
the VLVHC regulator 340 may include two or more coupled
inductor regulators 342 and 344 following an energy source
346. The coupled inductor regulators 342 and 344 are
preferably a buck version (2:1 regulator, 3:1 regulator, 4:1
regulator, etc.) of the coupled inductor regulator to take
advantage of the decrease in size of the output devices of the
energy source 346, however the scope of the invention includes
any embodiment of the coupled inductor regulator such as a
boost regulator having a 1:2 boost ratio.

[0077]   Figure 10B shows another aspect of a very low

voltage high current regulator 370 (VLVHC regulator) for

generating a low voltage output. The VLVHC regulator 370 is

similar to the VLVHC regulator 340 in function, except that

the VLVHC regulator 370 may include two or more coupled

inductor regulators 372 and 374 preceding an energy source

376. The coupled inductor regulators 372 and 374 may be any

configuration such as a buck configuration (2:1 regulator, 3:1

regulator, 4:1 regulator, etc.), a boost configuration (1:2

regulator), and a flyback configuration (1:-1 regulator) of

the coupled inductor regulator.

[0078]   Figure 11 shows an aspect of a multi-stage regulator

system 350 for converting an input voltage, Vin, to several

output voltages, Vout1-Vout3. The multi-stage regulator

system 350 may include an energy source 352 such as a buck

converter connected to two or more coupled inductor regulators

354-360. The multi-stage regulator system 350 may

advantageously generate several intermediate voltages such as

Vout1-Vout3, while minimizing the cost of the overall

implementation by reducing the cost of the output devices of

the energy source 352.

[0079]   Figures 12A and 12B show aspects of single supply

amplifier systems 400 and 410 for powering a load such as a

speaker 402 from a power amplifier 404. Conventional single

supply amplifier systems include a large DC blocking capacitor

in series with the load and power amplifier to remove any DC

components from the signal from the signal that drives the

load. The single supply amplifier system 400 advantageously

may use a coupled inductor regulator to generate a second

supply voltage, V_{o2}, from the first supply voltage V_{DD}. The

second supply voltage may be used to eliminate DC voltage from

appearing across the load 402.

[0080]   In one aspect, a 2:1 regulator 406 may generate a

voltage, V_{o2}, that is approximately one-half of the amplitude

of V_{DD}. The voltage, V_{o2}, may be applied to one end of the load

402 to bias the load 402 so that no DC voltage appears across

the load 402, thereby eliminating the need for a DC blocking

capacitor. In one aspect the 2:1 regulator 406 and the power

amplifier 404 may be fabricated on a single integrated circuit

401.

[0081]   In another aspect, a 1:-2 regulator 408 may generate

a voltage, $-V_{DD}$, that is the negative of the high side supply

voltage, V_{DD}, for the power amplifier 404. The voltage $-V_{DD}$ is

used as the low side supply voltage for the power amplifier

404 to convert the power amplifier 404 into a dual power

supply amplifier. The power amplifier 404 may then generate

generates an output that is approximately centered about zero

volts and has approximately no DC component, thereby

eliminating the need for a DC blocking capacitor. In one

aspect the 1:-1 regulator 408 and the power amplifier 404 may

be fabricated on a single integrated circuit 411.

[0082]   Figure 13 shows a vehicle electrical system 500 that

may be powered by a 24 volt battery 502. The vehicle

electrical system 500 may include a mixture of both 24 volt

loads 504 and 12 volt loads 506. For example, the basic

electrical systems of an automobile such as the engine,

compressor, fan, lights, and air conditioning may all be

driven from the 24 volt battery 502. Whereas, one or more

accessories for the automobile such as a stereo, computer,

cigarette charger, and global positioning system may have been

designed for a 12 volt automotive system and therefore require

a 12 volt supply to provide power. A 2:1 regulator 508 may

provide a low cost source of 12 volt power derived from the 24

volt battery 502 so that legacy automotive accessories that

require 12 volt power may.be employed in the automotive

electrical system 500.

[0083]   Figure 17A shows an aspect of an autosensing

regulator 510 for generating an output voltage, Vout, from an

input voltage, Vin. The autosensing regulator 510 is

particularly suitable for being used as the 2:1 regulator 508

in the automotive electrical system 500. The autosensing

regulator 510 may include an autosensor 530 to sense the input

voltage and control a 2:1 regulator 520. The 2:1 regulator

may be similar to the 2:1 regulator 20 in function with

corresponding elements numbered in the range 520-528. The

autosensor 530 may automatically control the 2:1 regulator 520

as a function of the amplitude of the input voltage. For

example, when Vin is greater than a predetermined voltage

level, the autosensor 530 may set the duty cycle of the

conduction switches 522a and 522b to 50% each so that the 2:1

regulator 520 may generate an output voltage that is

approximately one-half the amplitude of Vin, and when Vin is

less than the predetermined voltage level, the autosensor 530

may set the conduction switches 522a and 522b both to the

continuous on-state so that Vout is approximately equal to

Vin.

[0084]   Figure 17B shows another aspect of an autosensing

regulator 540 for generating an output voltage, Vout, from an

input voltage, Vin. The autosensing regulator 540 may include

an autosensor 560 to sense the input voltage and control a

conventional buck converter 550 as a function of the amplitude

of the input voltage. Any type of buck converter 552 may be

employed. The buck converter 550 may include a conduction

switch 552, a free-wheeling diode 554, an output inductor 556,

and an output capacitor 558. In one aspect, the autosensor

may set the conduction switch 552 to the on-state continuously

if Vin is less than a predetermined voltage level, and if Vin

is greater than the predetermined voltage level the autosensor

560 may enable the conduction switch to be driven by a

variable duty cycle signal to maintain a constant output

voltage.

[0085]   Figure 14 shows a driver power system 600 for

supplying power to a high speed line driver assembly (DDR)

602. A 2:1 regulator 604 may generate V_{TT} voltage from the V_{DDQ}

voltage. The V_{TT} voltage is approximately one-half of the V_{DDQ}

voltage. The 2:1 regulator 604 advantageously may use output

filter capacitors that are much smaller than conventional

regulators may require. The V_{TT} voltage may supply power to

termination devices 606a and 606b and the DDR 602. To

compensate for a V_{TT} voltage that is not precisely one-half of

the V_{DDQ} voltage, a reference voltage, V_{REF}, 608 for the DDR 602

may be derived from the VTT voltage. In addition, a filter

610 may filter the reference voltage 608 to attenuate noise

components.

[0086]   Figure 15A shows an aspect of a coupled inductor 700

wound on a torroid. The windings of the coupled inductor 700

are arranged so that DC currents flowing through the windings

cancel. By minimizing the combined DC current flowing in the

coupled inductor 700, saturation of the torroid is prevented

and high permeability materials such as ferrites may used for the torroid to reduce core losses.

[0087]   Figure 15B shows another aspect of a coupled inductor 710 wound on a planar assembly. The coupled inductor 710 is similar in function to the coupled inductor 700 such as the windings are arranged so that DC currents flowing through the windings cancel, so that high permeability materials such as ferrites may be used for the core.

[0088]   A number of embodiments of the invention have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention. Accordingly, other embodiments are within the scope of the following claims.